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AN INTRODUCTORY DISCUSSION OF THE ISENTROPIC CHART*

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-INTRODUCTION-

The isentropic chart, suggested by Shaw[1], has been developed recently in the course of an extensive program of research undertaken by Professor Rossby[2] at M. I. T., and is described herein as a means by which one may conveniently estimate air motions through utilization of available airplane meteorograph soundings and elementary physical principles. In addition, the chart aids the forecaster in visualizing where there will most probably occur certain meteorological activities, such as cloudiness, precipitation, icing, thunderstorms and cyclonic or anticyclonic circulation.

As yet, there have not been many investigations correlating these activities with the indications given by the isentropic charts; and since there are conditions in the atmosphere which impose limits upon their use, caution must be exercised and a background of experience established before one is justified in making forecasts on the basis of such charts. A thorough, critical and rigorous discussion of the limitations of the charts as an aid in forecasting is not practicable here; it is intended that this article set forth only the general meaning of what is portrayed on the chart and some of its possible applications, but the limitations in these respects must be kept in mind in the present state of knowledge and experience.

-- DEFINITIONS --

In order to avoid ambiguity, the following terms having application to the charts are defined:

A flow pattern is a schematic representation of the motion of given portions of the atmosphere. If a group of moving particles are observed for any given time interval and their paths plotted, the resulting representation of their trajectories is the flow pattern of the particles.

In order to draw flow patterns for atmospheric motion, it is first necessary to be able to define the stratum (sheet) in which the particles are to be found day after day, and second, to be able to identify particles as well as to distinguish them from others surrounding them. For this purpose, use is made of potential temperature and specific humidity.

The potential temperature of dry air is the temperature which the air would attain if it were brought adiabatically, (i. e. without gaining heat

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[1] Sir Napier Shaw: "Manual of Meteorology", Vol. III, 1930, p. 259 et seq.

[2] C-G. Rossby and collaborators : "Aerological Evidence of Large Scale Mixing in the Atmosphere", Transactions American Geophysical Union, 1937.

"Isentropic Analysis", Bull. Am. Met. Soc., vol. 18, June-July, 1937.

from or losing heat to external sources) from its prevailing conditions of temperature and pressure to some standard pressure, (usually 1,000 millibars). It remains unchanged throughout all dry adiabatic processes in which the air takes part.

An iso-potential-temperature surface, or, as it will hereafter be called, an isentropic[1] surface is defined as a surface in which all the particles or portions of the atmosphere have the same potential temperature. That is, it is a surface passing through all portions of the atmosphere that have one and the same potential temperature. Unsaturated air tends to remain in an isentropic surface as long as no external influences add or subtract heat. A stable atmosphere may be considered as a system formed by a succession of approximately horizontal isentropic surfaces (sheets) which lie above one another and are respectively characterized by higher potential temperature the greater the height. Such a system of isentropic surfaces forming a stable unsaturated atmosphere may be regarded as a constraint which permits neither the escape of contained particles nor the entrance of outside particles so far as each respective isentropic surface in the system is concerned. Under these conditions, if a particle were displaced from a given isentropic surface, it would encounter regions either potentially warmer or colder than itself and consequently, would tend by the resultant density difference to return to its own surface. For the same reason, particles outside the surface would be restrained from entering it. Therefore, aside from certain exceptions, which will be dealt with later, an isentropic surface satisfies the first necessary condition for drawing flow patterns of atmospheric motion, since it defines the stratum (sheet) in which the particles are to be found day after day.

Specific humidity is the mass of water vapor present in a unit mass of humid air. It follows that the specific humidity of a portion of air will be unaltered no matter how the shape or size of that portion is varied, provided its original composition remains the same. Therefore, barring changes in composition, it is then possible to use specific humidity for identifying portions of the atmosphere and for distinguishing one portion from another as they change position from day to day.

-- RESTRICTIONS --

The construction of flow patterns based on specific humidity and potential temperature is at times complicated by the occurrence of certain phenomena which are not in harmony with the assumptions that form the basis for the applications of the isentropic chart. The isentropic surface may be used to identify the stratum (sheet) for the flow pattern provided that no important amount of heat has been added to or subtracted from the air in that surface by external agencies, or by changes of state of any forms of water which are present and that no changes in the composition of the air have occurred. This means there must have been no condensation, evaporation, absorption, radiation or turbulent convection of consequence. Even though convection and condensation are ever-prevailing

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[1] Having equal entropy. If the potential temperature of dry air remains constant, its entropy remains constant.

conditions in the atmosphere, one is not entirely prevented from constructing flow patterns on that account. Where these conditions exist, the required flow pattern often may be considered nearly identical with that found in an isentropic surface chosen sufficiently high above the region of occurrence of the conditions as to be negligibly affected thereby. It has been indicated by various investigations that heat changes due to absorption, radiation, and evaporation can be considered negligible in this connection.

When observations reveal that condensation has occurred or that turbulent vertical motion may have influenced the surface, it becomes necessary to take these factors into account in the analysis of the flow pattern. In general, the effect of condensation is to lower the elevation at which given potential temperatures are found and to increase the specific humidity associated with them. Normally, in the atmosphere, potential temperature increases with height, while specific humidity decreases with height. When condensation occurs within a column of air, the potential temperature of each vertical portion is increased so that the original elevations at which the respective potential temperatures occurred become identified with higher potential temperatures, hence, as a consequence of the relationships specified in the preceding sentence, the various potential temperatures after condensation become identified with lower elevations and, therefore, generally with higher specific humidities. (When condensation occurs in a stratum without being accompanied by convective turbulence, the specific humidity will decrease near the top of the stratum, while the specific humidity will generally increase at lower elevations, owing to the resultant precipitation.) Figure 1 serves to illustrate these points.

On rare occasions, the vertical distributions of potential temperature and specific humidity may be just the opposite of the normal, so that the reverse of the above reasoning may apply; however, when the potential temperature decreases with height, convective turbulence usually occurs and the foregoing method of reasoning is then no longer applicable with regard to the effects of condensation. Convective turbulence can cause changes in the elevation and specific humidity of surfaces of given potential temperature which are positive, negative, or zero, depending on various circumstances, so that it is generally not possible to allow for this influence accurately, other than to observe whether unusual changes are accompanied by turbulence and can be explained thereby. In addition to the changes in specific humidity from the causes just noted, lateral mixing between adjacent portions of the atmosphere within the same isentropic surface greatly modifies the specific humidity distribution which identifies the daily flow patterns, and affords an explanation of certain types of air-mass modifications which have been heretofore difficult to estimate and have frequently even been neglected.

The analysis of the isentropic chart requires, especially when unexpected or unusual developments appear, that the observed values of the quantities be critically examined to determine whether or not there have been any violations of the principles upon the basis of which the charts are applied. If there have been any violations, the analysis must take them into account, otherwise, the results are likely to be misleading.

Present experience has shown, however, that even under unfavorable conditions, it is possible to construct flow patterns on isentropic surfaces which reasonably portray the daily three-dimensional motion of the atmosphere over the United States.

-- CONSTRUCTION OF THE CHARTS --

The completed charts, as drawn at present by the Meteorological Research Division of the Weather Bureau, include several auxiliary quantities which have given indications of value in forecasting. Since the application of isentropic charts is comparatively new, the procedure and the principles of interpretation to be described here may be considerably altered in the course of later experience and research.

The first consideration in the construction of the isentropic chart is the optimum choice of potential temperature such that the isentropic surface shall be least disturbed by the vitiating influences previously mentioned, viz., condensation, evaporation, radiation, turbulence, etc. The choice varies during the year, and so far, no standard surfaces have been chosen that satisfactorily meet all the requirements. The two most commonly used values of potential temperature in the summer months are 315 and 311 degrees, which, at this season, are found approximately at the mean altitudes of 3,000 and 2,000 meters, respectively. In the winter months, potential temperatures of lower value must generally be used.

It frequently happens that at some stations these values are not observed within the range of altitudes covered by the sounding; e. g., the 311 and 315 degree surfaces may be above the maximum altitude reached, or the potential temperatures from the ground up may be higher than the foregoing values. However, when isentropic charts are drawn separately for each surface, the difficulty, brought about by the higher of the two surfaces being above the maximum elevation of the sounding, can be reasonably adjusted by extrapolating the flow pattern in the lower surface to the higher surface, the assumption being that on the average the motion within and between the surfaces is similar. Where the potential temperatures under consideration are lower than those observed in the sounding at individual stations, that portion of the flow pattern for the regions where these stations are located is left blank. In the United States, this happens frequently in summer at such high-level stations as Cheyenne, Salt Lake City and El Paso.

Having thus arbitrarily chosen the 315 and 311 degrees potential temperature values to illustrate the construction of the isentropic chart, the routine procedure consists of entering the values of the related auxiliary quantities. To avoid confusion resulting from the tangle of many intersecting lines, three charts are made: First, the isentropic chart for 315 degrees is constructed by plotting the values of elevation above sea level, specific humidity, relative humidity, condensation level and wind that occur with a potential temperature 315 degrees, at the respective stations. Second, the isentropic chart for 311 degrees is plotted in the same manner. Third, a chart is plotted showing the difference in pressure between the 311- and 315-degree, or between the 309- and 313-degree, surfaces at each station, and the increase or decrease in this

value from the preceding day. Where data are not available for both the 311- and 315-degree surfaces, the 309- and 313-degree surfaces may be used in their stead, if practicable.

When the lapse rate is adiabatic, i. e., when the potential temperature does not change with height through a stratum, it is frequently difficult to select the appropriate values of the various elements for the isentropic surface corresponding to the constant potential temperature of the stratum. In such cases, it is customary to select values that conflict least with the continuity at surrounding stations and preceding charts.

Bearing in mind the limitations already explained, and making an effort to maintain continuity with the charts drawn on the preceding day, the analysis of the data on the isentropic charts requires judicious drawing of lines connecting points of equal values as follows:

(1) Lines connecting points of equal specific humidity; the appropriate values are written near the lines, and the regions of greatest moisture are marked "M" (moist), those of least moisture "D" (dry).

(2) Lines connecting points of equal elevation; the appropriate values are written near the lines, and the regions of greatest height marked "H" (high), those of least height "L" (low).

On the third chart, lines are drawn connecting points of equal (vertical) pressure difference between the two isentropic surfaces under consideration. Relatively speaking, stability between the surfaces is less near centers of maximum pressure difference than near centers of minimum pressure difference. On this <u>relative</u> basis, the centers of maximum difference may be marked "U" to designate "unstable or lesser stability" while centers of minimum difference may be marked "S" to designate "stable or greater stability". Centers of maximum positive change (increase) in the pressure differences from the preceding day may be marked "C", representing "convergent" and centers of maximum negative change (decrease) in the pressure differences may be marked "D" representing "divergent", to indicate the direction of change of air-mass distribution between the surfaces with time.

-- INTERPRETATION --

First, the lines of equal specific humidity portray the actual distribution of moisture over the country. Second, a good approximation to the flow pattern for any particular isentropic surface may be obtained by visualizing or plotting the (preceding) successive daily positions of given lines of equal specific humidity and regarding the flow of air particles as taking place along the line of the successive positions. The flow patterns can often be best determined when distinctive identifiable features in the configuration of the equal specific humidity lines, such as troughs, maxima, minima, etc., can be followed in their evolutions from

day to day. The streams of moist or dry air are identified between successive charts from considerations of historical continuity, bearing in mind the vitiating influences previously discussed. It is, of course, essential that the pertinent wind data be in harmony with the flow patterns deduced in the manner outlined.

The lines of equal elevation should be considered as contour lines showing the slope of the isentropic surface in which the portions of the atmosphere in its vicinity must move when motion relative to the surface occurs.

The relative humidity shows the nearness to condensation of each designated portion, and the condensation level shows the height at which such a portion would reach saturation if lifted.

The wind entries indicate the instantaneous horizontal motion at each station. (It is also desirable to enter wind data for surrounding stations. This can be done by interpolating from the wind charts for the elevations indicated by the contour lines of elevation at the locations of these stations.)

To interpret the wind data properly, the entire wind field must be taken into consideration, i. e., the winds occurring at all levels over the whole region being studied. The instantaneous wind data show only the <u>horizontal</u> directions and velocities of particles at given points. However, specific knowledge is required regarding the motion of particles with respect to the usual coordinate axes which run north-south, east-west, and vertical, or alternatively axes one of which is normal (perpendicular) to and the other two of which lie in the isentropic surface. The combined wind motions at, above, below and adjacent to individual points within any given isentropic surface may cause: (1) translation of the surface; (2) warping of the surface; (3) the displacement of particles within the surface; (4) acceleration or deceleration of either the particles or the surface itself, or both; (5) changes in density.

The rate of change of vertical velocity components with height may be estimated roughly from the relative motions in the horizontal wind field with the aid of the well known equation of continuity.[1] A simple notion of the application of that equation may be gained from the following paragraph.

Consider a horizontal plane (wind field) in which all the wind directions are the same but in which the velocities increase or decrease in the direction of motion of the air. Take any small region in that field and assume that the air density remains unchanged. Since the same amount of air must leave a given region as enters it, when the density remains constant, the equation of continuity leads to the conclusion that decrease

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[1] J. Bjerknes, "Practical Examples of Polar Front Analysis", Geophysical Memoirs, No. 50, London, 1930; and S. Petterssen, "Kinematical and Dynamical Properties of the Field of Pressure with Application to Weather Forecasting", Geofysiske Publikasjoner, vol. X, No. 2, Oslo, 1933.

of the horizontal velocity components in the direction of motion implies the existence of upward or downward motion away from the given horizontal plane in the region being studied, whereas increase of the horizontal components in the direction of motion implies upward or downward motion into the given horizontal plane.

If the given horizontal decrease or increase takes place in a short distance along the line of direction of motion, the vertical velocity change with given increment of elevation is greater than if the horizontal decrease or increase takes place in a longer distance. The components of the motion in the horizontal wind fields immediately above and below the given plane referred to in the foregoing must be studied in order to obtain at various heights the respective rates of change of vertical components with elevation.

When the horizontal wind field shows the motion to be everywhere uniform, the vertical components must be zero. Heights at which this is true serve as convenient reference points from which to deduce actual vertical components at neighboring points above and below. The components of the velocity up or down the slope of the isentropic surface may be estimated from the vertical components by resolving them along the direction of the slope.[1] [2] [3] It must be noted that with expansion of the air through motion up the slope of the isentropic surface, there is a tendency for horizontal divergence of the air, and with compression through downward motion, the opposite tendency prevails, viz., horizontal convergence.

When the actual wind fields are not as simple as the one assumed in the above discussion, and the air density changes, the problem of estimating vertical components and the various effects of the combined wind motions enumerated earlier, becomes more involved. In practice, the solution must be worked out from experience and the indications of other elements, such as pressure tendencies, convergence and divergence shown by the third chart, etc.

In the third chart, the vertical pressure differences between the two isentropic surfaces under consideration give an estimate of the actual distribution of the amount of air between the surfaces as well as a relative measure of the instantaneous stability as previously explained. The changes of these pressure differences from the preceding day give some indication of the time-rate of horizontal convergence and divergence of the atmosphere between the surfaces.

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[1] see: Petterssen, loc. cit., p. 37, and 62 et seq.

[2] An alternative proposal is given by R. B. Montgomery, "A Suggested Method for Representing Gradient Flow in Isentropic Surfaces", Bull. Am. Met. Soc., vol. 18, June-July, 1937.

[3] See also V. Bjerknes and collaborators, "Dynamical Meteorology and Hydrography, Part 2: Kinematics", Carnegie Institution of Washington, 1910 (especially Chapter 11).

-- APPLICATION --

All of the foregoing representations on the charts suggest logical interpretation with respect to forecasting; but it must again be emphasized that sufficient experience is lacking at present to realize all the possibilities and short-comings of the method. The following considerations represent an attempt at such an interpretation in which regions of greatest and least probable activity are differentiated only qualitatively, generally on the assumption that the 24-hour motion inferred from the flow pattern of one day will continue to the next, but making whatever modifications seem called for by the existing conditions.

If the wind data and the slope of the given isentropic surface indicate that the atmosphere is being lifted to higher levels, it is to be expected that, due to adiabatic cooling the actual temperature will approach the saturation point and that condensation with or without precipitation will take place, provided the elevation to which it is lifted is at or above the condensation level. On the isentropic chart, condensation areas can be estimated by considering the ascending motion of portions of the atmosphere along the isentropic surface or the ascending motion of the surface itself. The isentropic charts for the period from August 3 to August 6, 1937, inclusive, accompanying this article show a remarkably close agreement between the indicated regions of saturation and the actual precipitation and cloud areas on succeeding days.

An example of estimating condensation from the indicated ascending motion of portions of the atmosphere up the slope of an isentropic surface can be readily seen on the 311-degree isentropic chart for August 3. At Omaha the portion of the atmosphere in the given surface is characterized by a specific humidity of 12.4g/kg, relative humidity of 55% and is moving upward, as indicated by the wind field, from an elevation of 1530 meters toward Chicago where the elevation of the surface is 3190 meters. The indicated saturation level of 2660 meters at Omaha is found to be about half-way between the two stations along the slope of the surface, and it follows that condensation is probable in this region. The precipitation and cloud areas for the next day on the surface synoptic map verify this conclusion.

An example of estimating condensation due to lifting of a portion of the atmosphere by the motion of an isentropic surface is shown to some extent on the 311-degree isentropic charts for August 4th and 5th. Although this situation is not the best for the purpose, it illustrates that it is possible for particles of air to be moved vertically while remaining over the same geographical location either (a) by upward or downward motion of the isentropic surface itself (warping, with the particles fixed in the surface), or (b) by translation of the sloping isentropic surface (wedge-action, with the surface moving horizontally relative to the particle, but the latter remaining in the surface): Particular note may be made of the situation near Chicago on August 4, where the specific humidity was 3.1 and the surface was at an elevation of 3030 meters, while on the following day, the specific humidity was practically the same, viz., 3.0, but the

elevation had risen to 3900 meters. On August 5th, the 311-degree isentropic surface from Detroit to Nashville associated with the region marked "H" (high) sloped downward from 3090 meters at Detroit to 2850 meters at Nashville. This high region evidently had progressed southeastward from the vicinity of Fargo since the preceding day. It might be expected that the rising motions of air particles in the 311-degree isentropic surface observed at Chicago between August 4th and 5th, would continue with advance of the high region, and be observed at more southern stations on the 6th, accompanied by somewhat increased relative humidities, possibly reaching saturation. That this expectation was fulfilled may be seen from the changes which were observed at Nashville from August 5th to 6th. This type of lifting appears frequently to be associated with thunderstorms which develop along cold fronts. The surface synoptic map of August 6th, presents an example of this correlation. Other types of lifting may also occur by favorable combinations of motion of particles relative to but within the isentropic surface and of motion of the isentropic surface relative to the earth.

It is necessary at this point to justify the application of the isentropic chart to cases where condensation has occurred as illustrated above. Since the occurrence of condensation on the isentropic surface is a violation of the principles upon which the chart is applied, it would appear that the usefulness of the chart must be lost under such conditions. However, as has been stated earlier, it can be assumed that the flow pattern, contour lines, and motion pertinent to one high isentropic surface are representative to a good degree of approximation of the same elements in adjacent lower surfaces, even though condensation has occurred in the latter but not the former. Under these circumstances, tendencies for continuing condensation or clearing in the lower surfaces may be implied by ascending or descending motions of air, respectively, in the higher surface where condensation is not present. Also, even though condensation may eventually occur within a particular surface, the assumptions under which the chart is applied can be considered valid until the phenomenon actually takes place. A close examination of all the accompanying charts, which were chosen at random, show how substantially the stated method of applying data from one surface to another is supported, even though there may be occasions when it does not hold completely.

The foregoing concepts should enable the airway forecaster to estimate the probable approximate extent and height of cloudiness. The isentropic chart furnishes a means of visualizing the major features of the atmospheric processes involved in the formation of clouds, precipitation, etc. With this as a background, it is necessary to consider also various factors which are effective in producing complications, for example, conditional and convectional instability, turbulent vertical motion, convergence and divergence with their resultant stability changes, nonhomogeneous eddies, wind gradients, stratification, topography, effect of condensation and precipitation, etc. The following simplified treatment does not deal with any of the above influences, but nevertheless, it provides an idealized basis upon which a forecast may be made and modified according as the various factors are thought likely to become effective.

Let us considor how one may approximate the probable area within which condensation will occur near a given isentropic surface. Let us take one small unsaturated portion of the atmosphere near some given station, and assume that the wind data indicate it will move in a definite path within, but relative to its appropriate isentropic surface, at least while it remains unsaturated. Assume that at some point along its path this portion will reach its condensation[1] level by arriving at an environment of sufficiently low pressure.

Now we may contemplate two extreme conceivable possibilities regarding the condensation phenomena beyond the level in question: (a) products of condensation are wholly carried along with the moving portions of atmosphere in which the condensation occurred, i. e., the adiabatic, reversible, rain or snow stage[2] prevails, and (b) products of condensation fall away as rapidly as formed from the moving portions of atmosphere in which the condensation occurred, i. e., the pseudoadiabatic, irreversible, rain or snow stage[2] prevails.

If the condensation level is passed, and the adiabatic (reversible) saturated stage prevails, continued motion of the portion of atmosphere will result in further condensation so long as the (environmental) pressure is progressively lower along its path, while condensation will remain associated with the portion in question so long as it is in an environment at a pressure lower than that existing at the condensation level. When the pressure is progressively higher along its path, the cloud particles are evaporating. (see Fig. 2) Therefore, in the adiabatic, saturated stage, the area extending from the condensation level to the point where evaporation is completed, namely at a pressure equal to that at the condensation level, defines the region of cloudiness appropriate to the portion of atmosphere under consideration. In estimating the area of condensation appropriate to this portion, allowance must be made on the one hand for the expansion of the air and the associated divergence with decrease of pressure; on the other hand, for contraction and the associated convergence with increase of pressure. By a similar procedure, the regions of cloudiness for neighboring portions of the atmosphere may be defined. The total area found by combining all the regions thus determined is the approximate extent of expected cloudiness resulting from condensation of water vapor contained in air portions originally associated with the given isentropic surface. The portions which will not reach sufficiently low pressure to cause saturation will be free from cloudiness. It should be noted that the motion of the portions containing products of condensation will not be confined to the original isentropic surface but will take place in a higher surface of appropriate thermodynamic characteristics intersecting the former surface at the condensation (pressure) level. This follows because the liberation of latent heat by condensation makes the air portion warmer and hence less dense than its environment in the isentropic surface, whereby it must

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[1] The condensation level should be considered as the pressure to which the air must be expanded in order for condensation to begin.

[2] W. J. Humphreys, "Physics of the Air", 2nd Edition, 1929, p. 253-257.

rise to some higher level at which density equilibrium is reached. The path along which this equilibrium with respect to the surrounding atmosphere is progressively maintained, defines a strip in the surface of actual motion of the saturated air.

Considering the second alternative, if the condensation level is passed and the pseudoadiabatic (irreversible) stage prevails, continued motion of the portion of atmosphere will result in further condensation only as long as the pressure at successive positions in its path is progressively less. On the other hand, any motion thereafter in which the environmental pressure is progressively higher along its path will give rise to practically immediate evaporation of the small amount of condensation products associated with the portion in question since the major quantity of these products has fallen away. Wherever the highest saturated portion reaches this condition, the upper limit, in general, of the clouds is defined. Analogously to the case of the reversible stage, the motion of the air portions will take place above the original isentropic surface along a surface having appropriate thermodynamic characteristics, but this newly specified surface for the pseudoadiabatic stage is only slightly lower than the surface of motion pertaining to the adiabatic, saturated stage. To a close degree of approximation, the new surface in question is one of constant equivalent-potential temperature when the condensation is in the liquid form.

Since it may be expected that neither will all the products of condensation be carried along with the moving portions of air nor will they completely fall away, the actual process is, presumably, intermediate between the two limiting ones described above, although probably nearer the pseudoadiabatic process in general.[1]

The precipitation of the condensation products from the moving portions of atmosphere introduces complications regarding the extent of clouds at low elevations and other related factors such as increase of specific humidity, and changes in potential temperature, stability, etc. largely due to evaporation of these products; for example, the air flow at these elevations may cause spreading of the cloudiness over contiguous areas not in the direction of the upper air flow. However, some deductions may be made concerning these phenomena with the aid of the wind data, the flow patterns shown in connection with unaffected adjacent isentropic surfaces, the topography of the lower isentropic surfaces, and other pertinent information, tempered by experience.

When there is evidence or likelihood of marked conditional instability in a region where condensation is likely to occur, the possibility of penetrative convection with the development of cumuliform clouds requires consideration.

It should be emphasized that the study of isentropic charts and other appropriate data for several levels is necessary in order that the vertical, as well as the horizontal extents and natures of the various phenomena in question may be correlated. That is, the problem must be considered from a three-dimensional standpoint.

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[1] See Humphreys, loc. cit. p. 257. and Sir N. Shaw, "Manual of Meteorology" vol. III, 1930, p. 251.

One may approximate the extent and height of intermediate clouds from the isentropic chart by extending the preceding considerations to the lowest isentropic surface which can be considered reasonably free from the effect of ground influences. Roughly speaking, when isentropic surfaces are lower than about 1000 meters, they are excluded as unsatisfactory for our purpose, at least in summer.

Figures 2 and 3 illustrate the essential features of the foregoing treatment. Figure 3 is a qualitative idealized vertical cross-section obtained by extrapolating the lower potential temperature isotherms (viz. 307°-303°) from the 311- and 315-degree isentropic charts for the strip between say Chicago and Washington. (Similar cross-sections are, of course, drawn most accurately on the basis of aerological data from stations at close intervals along the line of the section. However, cross-sections can be obtained for lines along which no stations occur, when isentropic charts are available for the general area in question. This may be done after noting the data indicated on the isentropic charts along the line representing the intersection of the vertical cross section with the surfaces.) The cross-section shows a current of warm moist air (TA) which is preceded by a transitional mass of cool, drier air (NPC) and followed by a fresh outbreak of cold and dry air (PC). The arrows indicate the motion of the atmosphere relative to the surfaces and for simplicity, it is assumed that the motion of the particles within the surfaces is everywhere uniform in direction and velocity, viz. 20 miles per hour. The condensation levels of portions at Chicago on the diagram are marked with dotted lines and are indicated by primed letters where they intersect their respective isentropic surfaces. These levels should be determined from airplane data pertaining to stations from which the air will arrive at the forecast area during the forecast period. As each portion of the atmosphere moves from west to east, the portion marked "D" will reach its condensation level first. This will occur after the motion has continued about 200 miles or after ten hours and will take place at an elevation of 4700 meters. The portion marked "C" will then reach its saturation level at 3200 meters after the motion has continued about 230 miles or 11-1/2 hours. Similarly, for other portions until the portion "A" at the lowest elevation above ground effects will become saturated at 1300 meters about half way between Chicago and Washington and approximately twenty hours after the time of the airplane observations. The above demonstration is an idealized one, in which each isentropic surface is treated separately, which makes it appear that clouds would form in layers, one for each surface. It is obvious that there is an infinite number of isentropic surfaces between those shown in the diagram, wherein clouds would occur if the uniform motion actually prevailed. In natural cases, the non-uniformity of the pertinent meteorological elements causes cloudiness to occur in definite layers when there is adiabatic cooling and the saturation levels are reached. However, with such modifications, as allowing for the true vertical moisture and wind distribution, etc., the idealized approach described above affords a logical contribution to the problem of cloud and ceiling forecasting.

The estimation of the probability of hazardous ice conditions requires the use of some method which will indicate where the condensation regions are near freezing temperatures,[1] i. e., temperatures ranging from 0 degrees to about minus 12 degrees, Centigrade. Such a method may be based on the isentropic chart. It can be seen from the pseudoadiabatic diagram that the 0-degree isotherm intersects the potential temperature isotherms (adiabats) at certain definite respective pressures; for example, the 0-degree isotherm intersects the 311-degree adiabat at a pressure of about 636 millibars. It has been found that the elevation at which this pressure occurs varies from day to day but that for temperatures in this range, this elevation rarely undergoes a total variation of more than 150 meters. Therefore, as a first approximation, it can be said that whenever the 311-degree isentropic surface is as high as, or higher than the average elevation, viz., 3850 meters, freezing conditions are likely. The following table shows the range of elevations for difference isentropic surfaces where freezing conditions are probable:

Potential Temperature θ	Range of elevations for freezing conditions 0° to -12°C. (meters, m.s.l.)
°Abs.	
315	4150 - 5350
311	3850 - 5050
307	3450 - 4800
303	3100 - 4500
299	2750 - 4100
295	2350 - 3800
291	1900 - 3500
287	1450 - 3000

NOTE: The above table is based on inadequate data and needs to be more fully verified.

Whenever the elevation of any particular isentropic surface is found to be within the above limits, freezing conditions are possible. Applying this reasoning to the idealized diagram in figure 3, freezing conditions would be thought likely in the 311-degree surface, beginning at the elevation of 3850 meters near Pittsburgh and in the 315-degree surface, beginning at the elevation 4150 meters near Chicago. Ice conditions would not be thought likely in the 315-degree surface until the portion reached its condensation level at 4700 meters, as indicated on the diagram. Isentropic surfaces lower than the 307-degree surface would likely be free of icing.

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[1] L. T. Samuels, "Meteorological Conditions During the Formation of Ice on Aircraft", Tech. Notes #439, National Advisory Committee for Aeronautics, Dec. 1932, Washington, D. C.

Sometimes the slope of isentropic surfaces is very flat and the surfaces just reach the lower limits of elevation for freezing or condensation. Clearly, the estimate of the extent of icing or cloudiness is then not so definite as when the slope of the surface is steep and the surfaces extend well above the limits of elevation for freezing or cloudiness.

Another application of the isentropic chart is with respect to thunderstorms. It appears probable that thunderstorms are most likely where the following conditions are fulfilled:

(a) Vertical convection vigorous in lower levels.
(b) Quantity of water vapor transported upward relatively large.
(c) Condensation level is reached preferably at relatively low altitudes.
(d) The lapse rate is relatively large so that the instability realized above the condensation level is considerable.
(e) The vertical temperature distribution is such that the convection of air will extend up to relatively high altitudes.

The first two of these considerations are most nearly fulfilled wherever air of moderate or high specific humidity, preferably the latter, is actively ascending the steepest slope of the isentropic surface. The third condition is shown on the isentropic chart to be satisfied when the saturation level for the moist ascending air would be reached, preferably at low altitudes, by continued motion up the isentropic surface. The fourth condition regarding stability may be studied by the use of an energy diagram or by the use of a chart showing vertical distances or pressure differences between neighboring isentropic surfaces. The most stable regions of the atmosphere are those regions where the increase of potential temperature with elevation is greatest and vice versa. In other words, conditions are most stable where the isentropic surfaces are vertically closest to one another, and least stable when they are vertically farthest from one another. If the portions of atmosphere within two neighboring isentropic surfaces are moving in such a way as to cause increase or decrease of the vertical distance between the surfaces (vertical stretching or shrinking), the stability of the air between them will decrease or increase respectively. Therefore, there is a tendency for the fourth condition, regarding thunderstorm development, to be satisfied wherever increase of these distances is indicated. The fifth condition, concerning thunderstorms, may be studied, of course, by the use of an energy diagram as an auxiliary chart.

As stated before, the third chart drawn in the Meteorological Research Division shows regions of greatest and least pressure differences between two isentropic surfaces, and the regions of greatest positive and negative daily changes in these differences. It also portrays the thickness or mass distribution, and with certain exceptions, the daily rate of lateral convergence and divergence of the atmosphere. As such, this chart, taken in conjunction with the isentropic charts and the motions shown thereon by the wind data, can be used to indicate regions

where the air will most probably be relatively stable or unstable, with attendant possible thunderstorm development in the latter case. The indications in this respect are well supported for the period from August 2 to August 6th, as can be seen by comparing the accompanying charts with the occurrence of thunderstorms. In nearly every case on these charts, thunderstorms can be associated with areas where the atmosphere is shown to be moving from regions of least pressure difference to regions of greatest pressure difference. It frequently happens that the observed pressure differences and changes at individual stations are not representative, due to the disturbing influences already mentioned, such as condensation, turbulence, etc., and, therefore, the chart can be misleading if some allowances are not made for these influences.

Finally, indications may be obtained from the isentropic charts concerning the estimation of probable regions of cyclonic and anticyclonic genesis and circulation. Preliminary experiments and theoretical investigations undertaken by Professor Rossby have led to certain conclusions regarding the relations of the above activities to the changes in vertical distance or pressure between isentropic surfaces under the influence of lateral stresses. The Weather Bureau is making some use of these relations, which seem to show a simple direct connection between the cyclonic vorticity and the change in vertical distance or pressure between two isentropic surfaces, such that positive (+) changes in this distance or pressure are associated with an increase in cyclonic vorticity and vice versa. It is expected that an early paper by Professor Rossby will give considerable attention to these phenomena in particular, and also to a more detailed treatment of all the foregoing considerations.

-- CONCLUSION --

The preceding pages have described and illustrated an easily constructed chart which has as its first objective the portrayal in a readily-grasped manner of how the lower atmosphere moves from day to day. It has been shown that portions of the atmosphere can be identified by means of two quantities, potential temperature and specific humidity, which when used in accordance with the principles set forth, quickly reveal configurations which aid in obtaining reasonable approximations to the actual flow patterns of atmospheric motion.

Although there are factors which cause some difficulty, the results thus far obtained are promising and enlightening. When the accompanying charts are closely studied, many interesting features can be found which have not formed a part of this article, such as, the alternate outbursts of moist and dry regions and the lateral mixing which seems to occur as these outbreaks become isolated from their original sources; the eddy-like motion which follows consistently from day to day, and the independence of this motion from the movement of pressure areas at the surface of the earth. The further study of such observations may afford a better understanding of what actually takes place in the atmosphere.

Without doubt, the motion shown by the flow patterns and the fundamental principles underlying the analysis of them give a clearer understanding of large scale meteorological activities than has heretofore been available with other methods of representation. The interpretation of the chart with regard to the atmospheric activities discussed in this article are based on simple physical principles. With the further development of the charts and more experience in their use, it is hoped that they will provide an approach to the solution of many major meteorological problems.

The writer is greatly indebted to Mr. L. P. Harrison for many constructive suggestions and valuable aid in the preparation of this article. Acknowledgment is also due to Drs. H. R. Byers and E. W. Woolard, and Messrs. W. P. Day, D. M. Little, C. L. Mitchell and R. H. Weightman for useful comments, criticisms, and suggestions leading to its improvement.

NOTES REGARDING FIGURES 1, 2, AND 3

Figure 1: Potential temperature (°Absolute) and specific humidity (g./kg.) respectively, plotted against height, both before and after condensation. For simplicity, the same change due to condensation is assumed for all heights. Effects of convectional turbulence are assumed to be negligible.

Figure 2: Idealized vertical cross section through the atmosphere showing curves which represent the intersections of the vertical section with various surfaces in which portions of the air might move under certain conditions, with possible attendant condensation phenomena. Only relative motion of the air portions from left to right with respect to the surfaces is portrayed. A symmetrical distribution of meteorological conditions is assumed to prevail before condensation, i. e. symmetrical horizontally about the line extending vertically downward from the highest point of the original isentropic surface.

Curve a designates the relative trajectory the air portions would follow when saturated, if the products of condensation were wholly carried along with the portions, i. e. if the adiabatic, reversible, (saturated) rain or snow stage prevailed. This is a theoretical extreme probably never actually reached, and is approached only when the condensation particles are of extreme smallness.

Curve b (dashed) designates the actual relative trajectory the saturated air portions follow while a considerable fraction of the products of condensation fall away as rapidly as formed, and a small fraction is carried along with the air portions. Point d designates the place at which evaporation of the condensation products is complete. Beyond that point, the path for the then unsaturated air portions is in an isentropic surface.

Curve c designates the relative trajectory the air portions would follow if all the products of condensation fell away as rapidly as formed, i. e. if the pseudoadiabatic, irreversible, rain or snow stage prevailed. Saturated conditions exist along this path from the condensation level to the level of minimum pressure (generally maximum elevation), while unsaturated conditions exist beyond the latter level in the moving air portions. The path beyond the latter level is, therefore, along an isentropic surface. The path c up to that level is a theoretical extreme closely approached in nature by the actual path b, especially when the condensation particles are relatively large. Along path c the equivalent potential temperature is approximately constant, assuming condensation products to be in the form of liquid water.

NOTES REGARDING FIGURES 1, 2, AND 3 (Continued)

Figure 3: Vertical cross-section through the atmosphere showing isentropic surfaces (303-315°) before condensation occurs. The arrows indicate motion of portions of air relative to the isentropic surfaces. For simplicity, motion of the surfaces relative to the earth is neglected in the diagram.

CG = Chicago, Ill.; CO = Columbus, O.;
PT = Pittsburgh, Pa.; WA = Washington, D. C.

The dashed curves correspond to curve (b) of Figure 2.

A', B', C', and D' are the condensation levels of portions of air originally at A, B, C, and D, respectively.

The data in miles given below the figure 790 mi. represent the horizontal distances which would be traveled in a straight line by the portions of air moving in the isentropic surfaces from Chicago to their respective condensation levels. The figures in parentheses (hrs.) represent the times required to travel these distances at a uniform rate of 20 miles per hour.

Note that icing may occur in the 311° isentropic surface at and above the 3850 m. (freezing) level; in the 315° surface, at and above the condensation level (4700 m.).

Where the condensation level is reached before the moving portions of air attain to a freezing condition (for example: 311° surface in Fig. 3), the place at which 0°C. occurs in the saturated portions traveling along the actual path of the (saturated) air (designated by the dashed curve, similar to b, Fig. 2) is not necessarily directly over the place where the temperature is 0°C. in the original isentropic surface. The actual and relative locations of the freezing points in (1) the actual path, (2) the original isentropic surface, and (3) the precipitating condensation products, respectively, depend on numerous factors such as the distributions of air density, temperature, humidity, wind, etc., and the effects of evaporation, convection, mixing, precipitation, etc.

When condensation occurs and the elevations of the affected isentropic surfaces change accordingly, (see Fig. 1), the geographic locations of points in these surfaces at definite temperature (e. g. freezing) also change, assuming the elevation at which such points are found remains essentially the same, hence some allowance must be made for this in estimating the locations where icing may occur. Similarly, the locations of points in each given surface at definite pressure also change. Hence, assuming the elevation at which such points are found remains essentially the same, some allowance must be made for this effect

NOTES REGARDING FIGURES 1, 2 AND 3 (Continued)

when estimating where a condensation level at the definite pressure will occur. This matter is especially pertinent when attempting to estimate where a freezing or condensation level will occur in a given isentropic surface while it may happen that a critical part of that surface will (before such level is reached by the associated moving portions of air) be affected by condensation products carried upward across it (i. e. the given isentropic surface) along a non-isentropic surface such as that designated by curve b in Fig. 2, or by such products falling into it from a higher level where condensation may be occurring.

Fig. 2 and 3: The vertical scale is greatly exaggerated relative to the horizontal scale, in order to increase the separation of the curves and to make the illustrations clear. With regard to the saturation curves a, b, c, and the dashed curves in Fig. 3, it should be noted that when the condensation is in the form of snow the curves should be slightly higher than when the condensation remains in the form of liquid water.

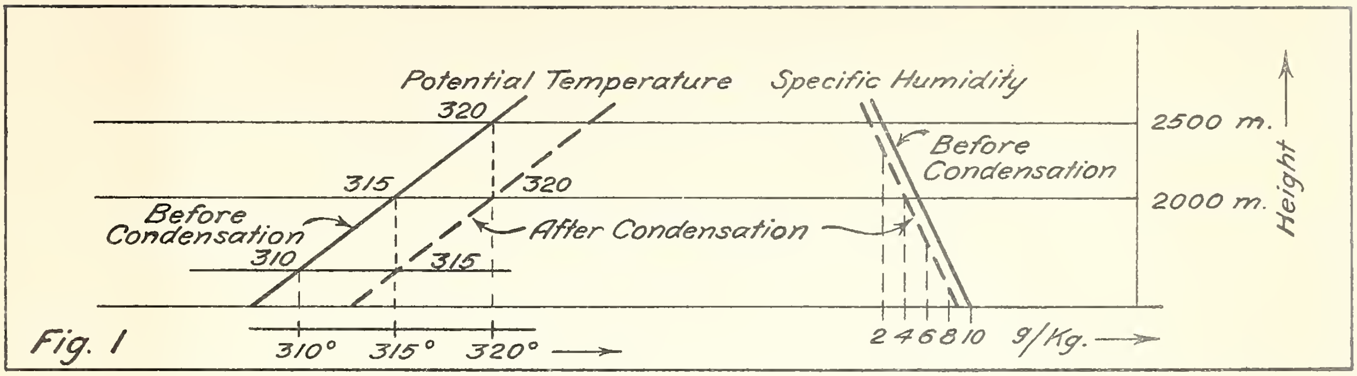


Fig. 1

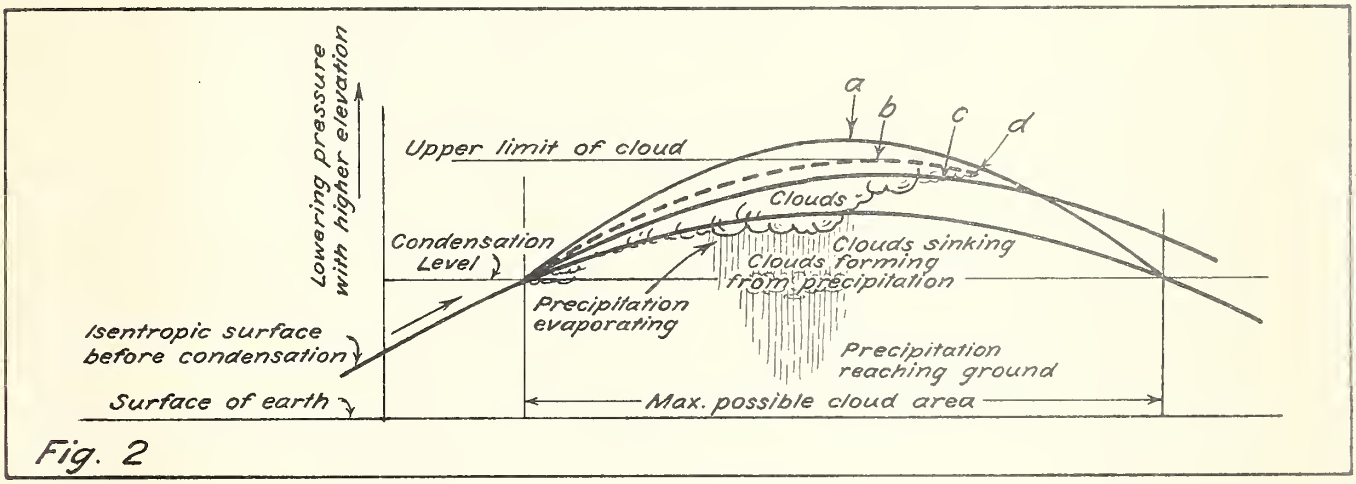


Fig. 2

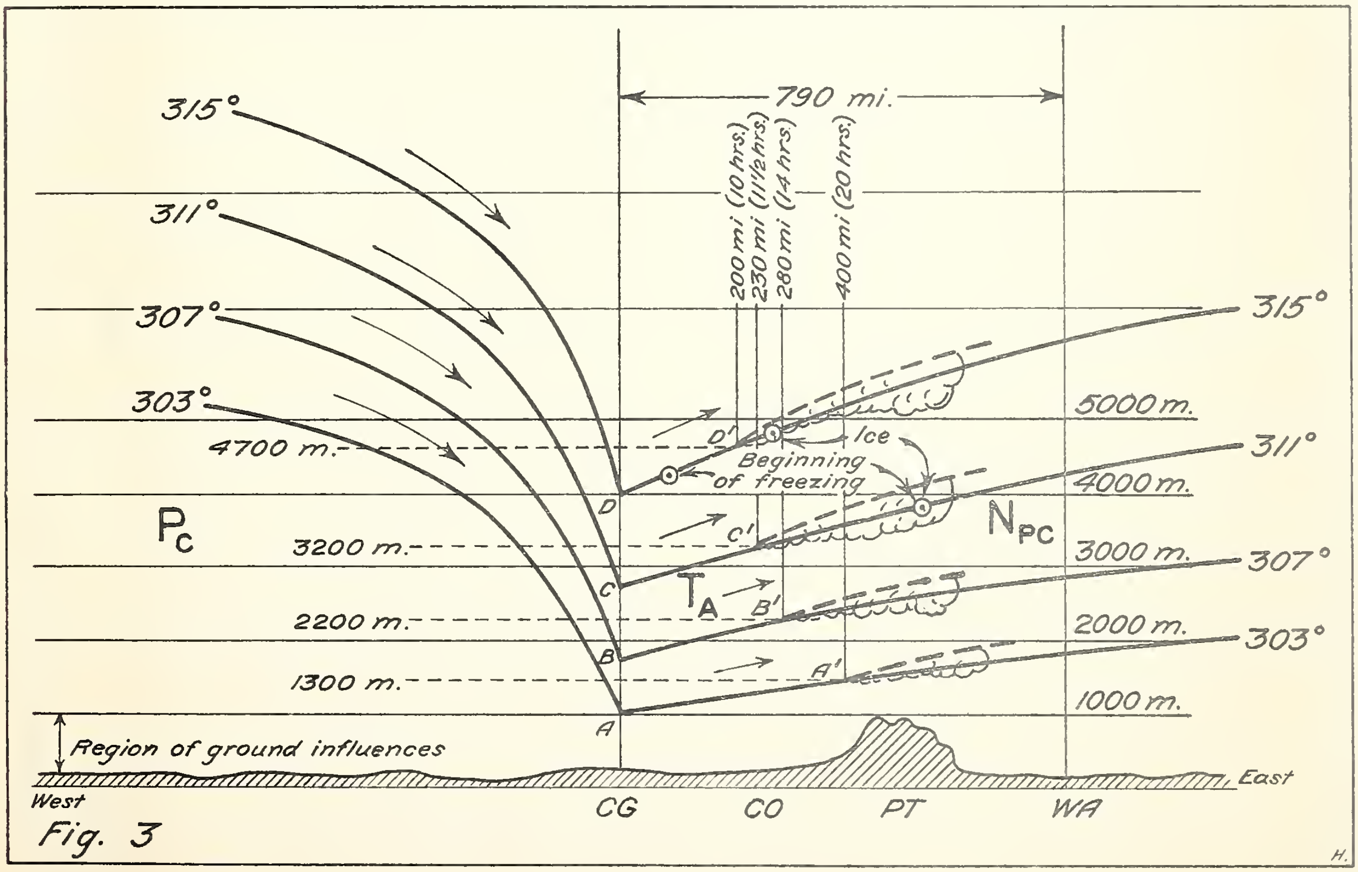
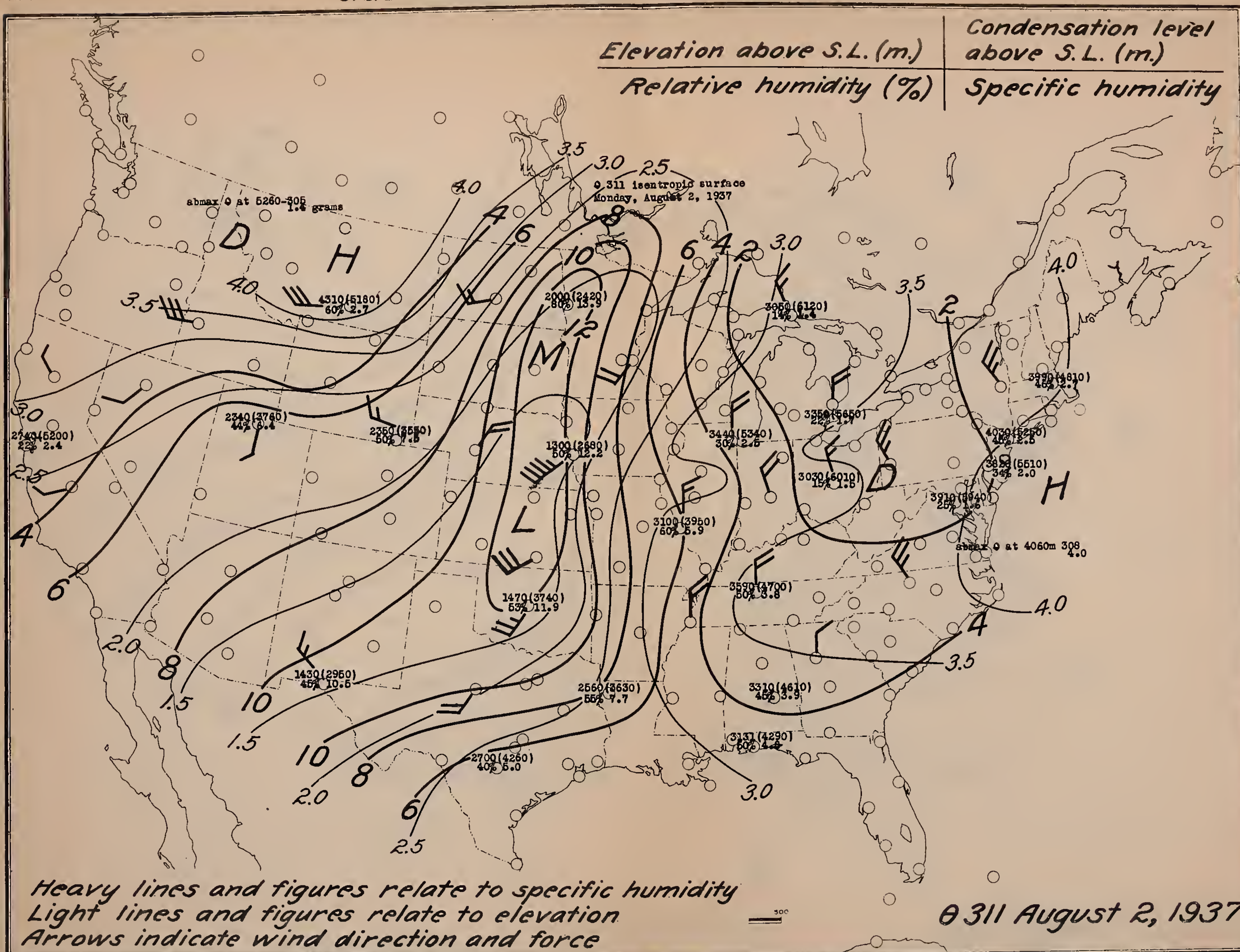


Fig. 3


Elevation above S.L. (m.)
Condensation level above S.L. (m.)
Relative humidity (%)
Specific humidity
θ 311 isentropic surface
Monday, August 2, 1937
abmax θ at 5260-305
1.4 grams
abmax θ at 4060m 308
4.0
4310(5180)
60% 2.7
2000(2420)
80% 13.9
3950(5120)
14% 1.4
3990(4810)
46% 2.7
2740(5200)
22% 2.4
2340(3760)
44% 3.4
2350(3550)
50% 7.5
1300(2680)
50% 12.2
3440(5340)
30% 2.5
3350(5650)
22% 1.7
3030(6010)
15% 1.5
3910(5940)
25% 1.5
3100(3950)
60% 5.9
1470(3740)
53% 11.9
3590(4700)
50% 3.8
1430(2950)
45% 10.5
2560(3630)
55% 7.7
3310(4610)
45% 3.9
3131(4290)
60% 4.8
2700(4260)
40% 5.0
Heavy lines and figures relate to specific humidity
Light lines and figures relate to elevation
Arrows indicate wind direction and force
θ 311 August 2, 1937

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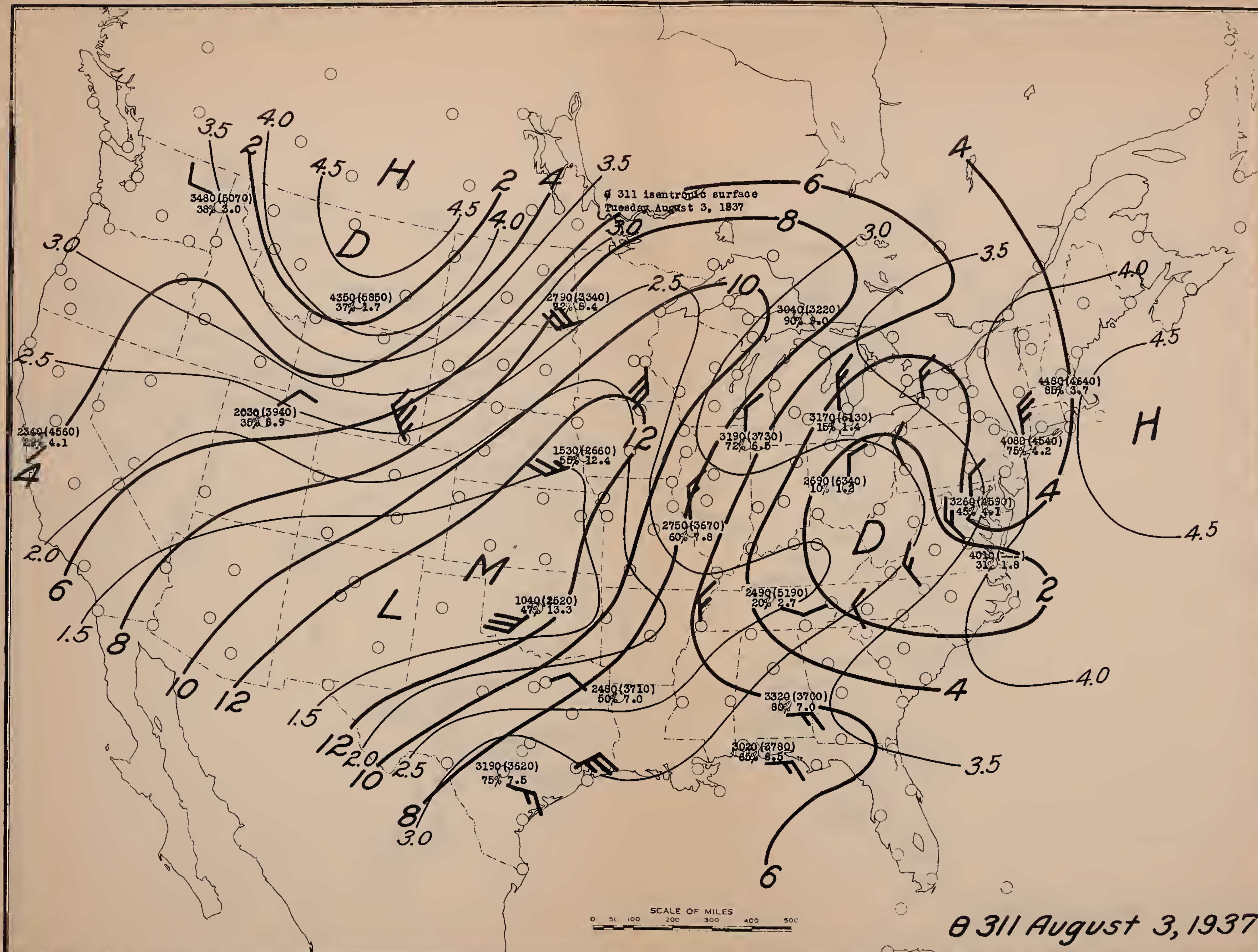

θ 311 August 3, 1937

MAP A1

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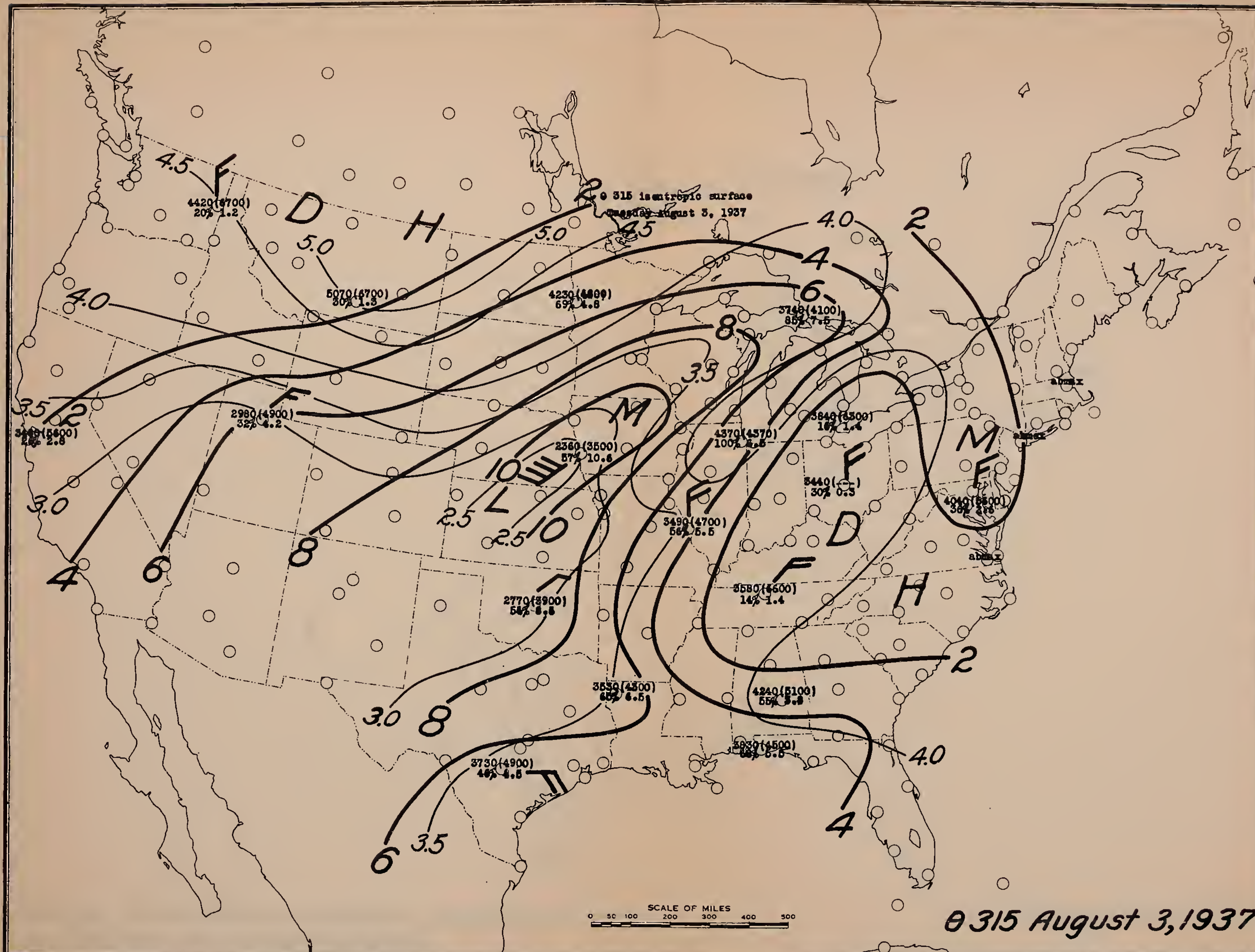

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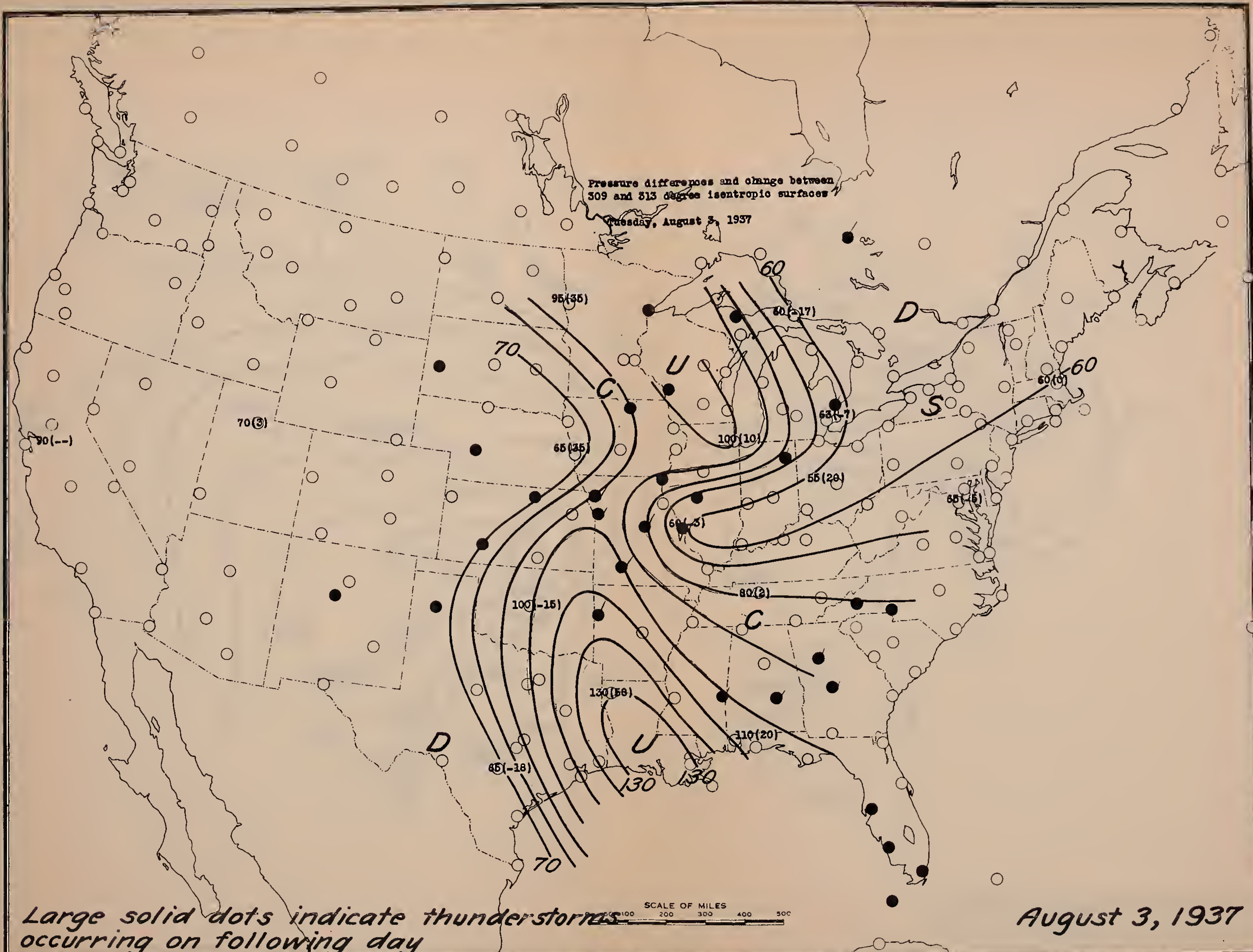

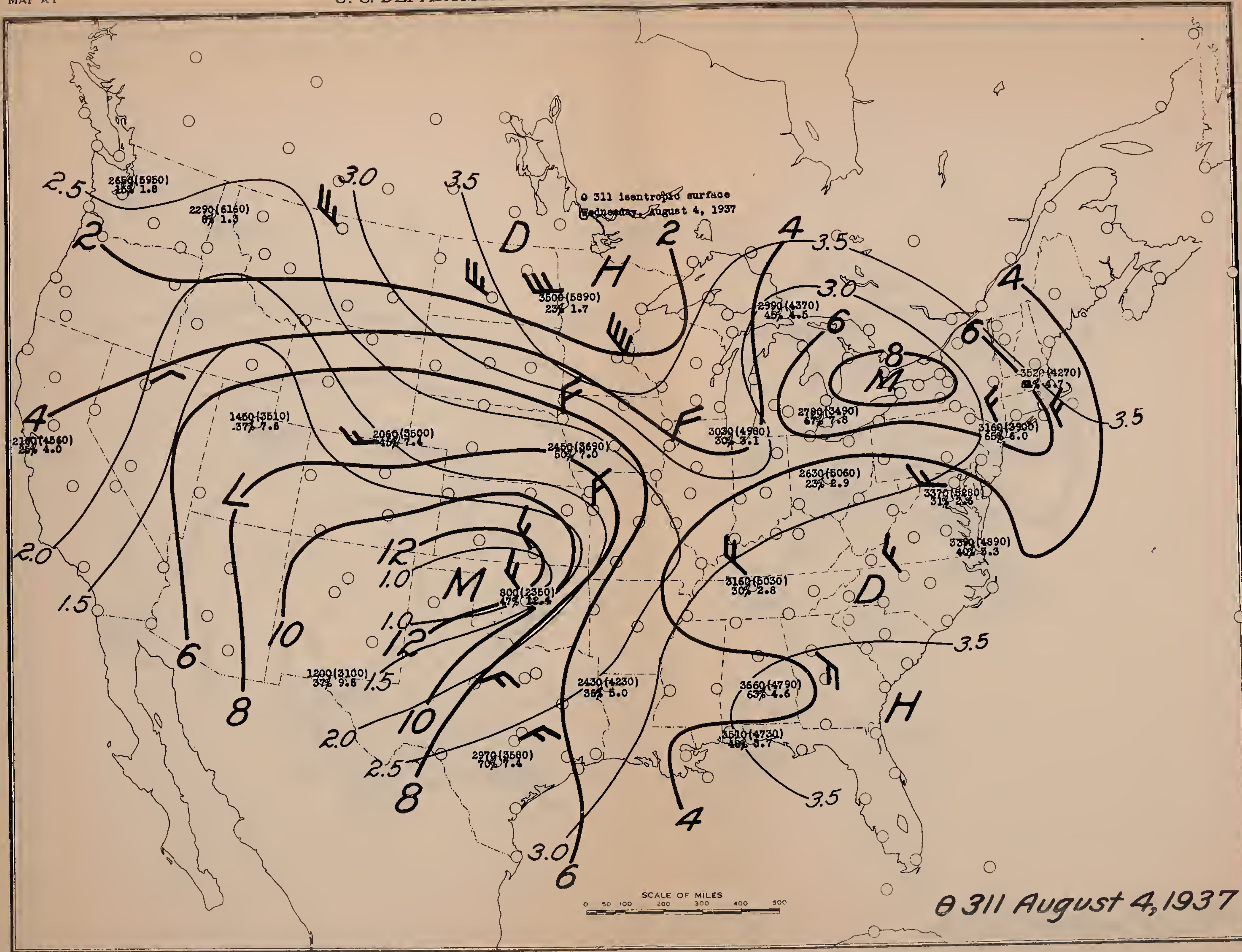
θ 311 isentropic surface
Wednesday, August 4, 1937
2290(6160)
3500(5890)
23% 1.7
2990(4370)
45% 4.5
1450(3510)
2060(3500)
2450(3690)
3030(4980)
30% 3.1
2790(3490)
3160(3900)
65% 6.0
3520(4270)
2630(5060)
23% 2.9
800(2350)
47% 12.4
3160(5030)
30% 2.8
1200(3100)
37% 9.5
2430(4230)
3660(4790)
63% 4.6
2970(3580)
70% 7.4
3510(4730)
3390(4890)
SCALE OF MILES
0 50 100 200 300 400 500
θ 311 August 4, 1937

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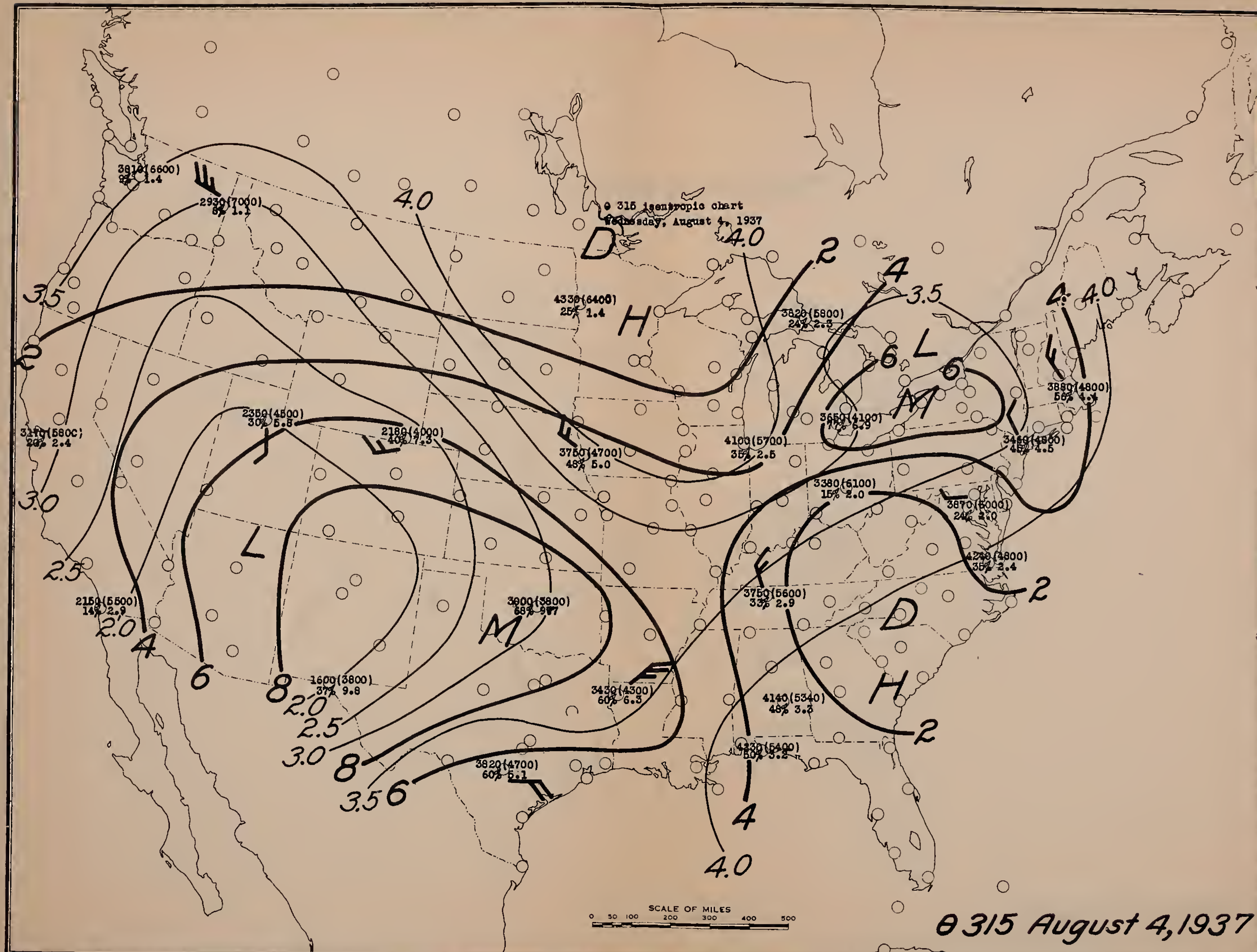
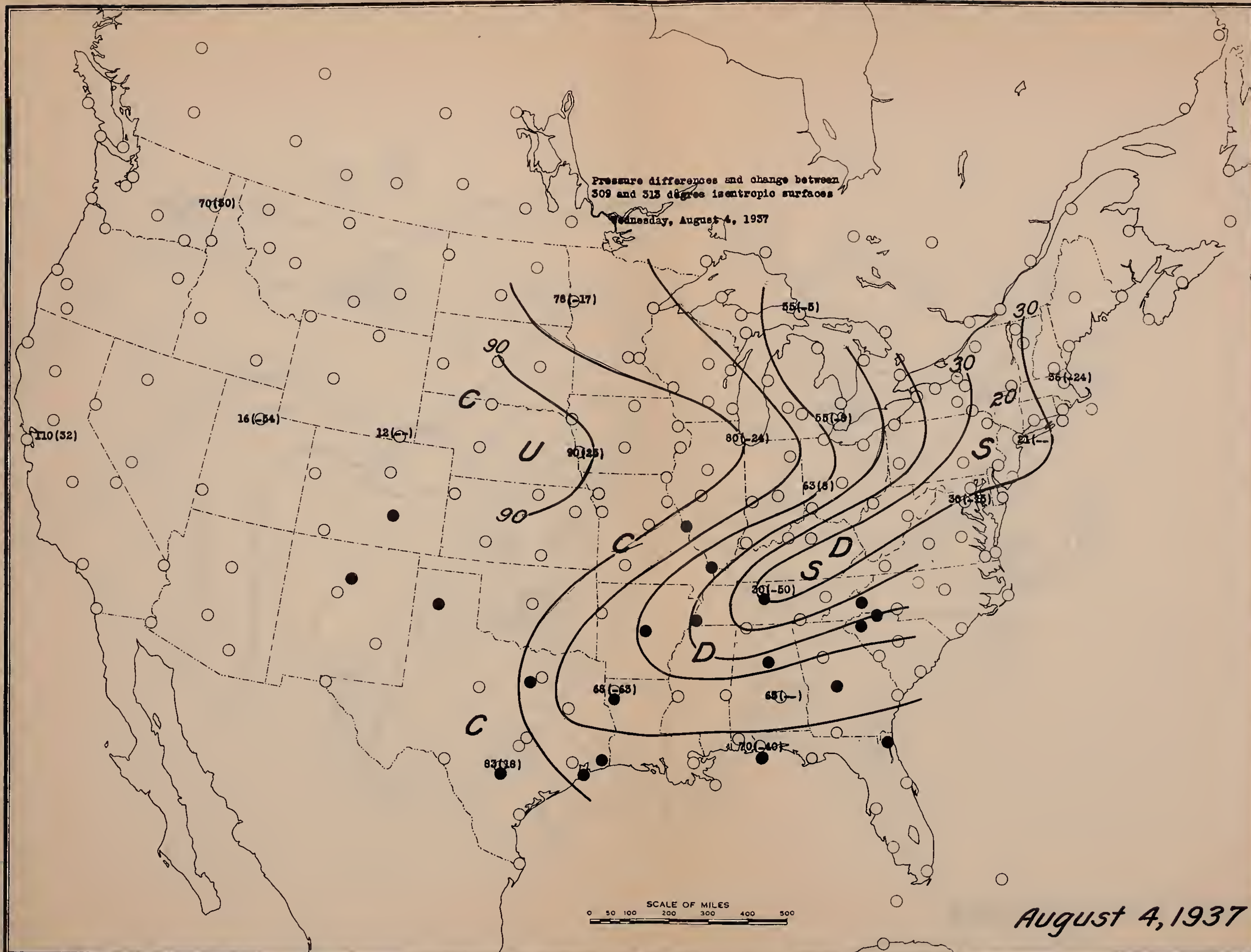
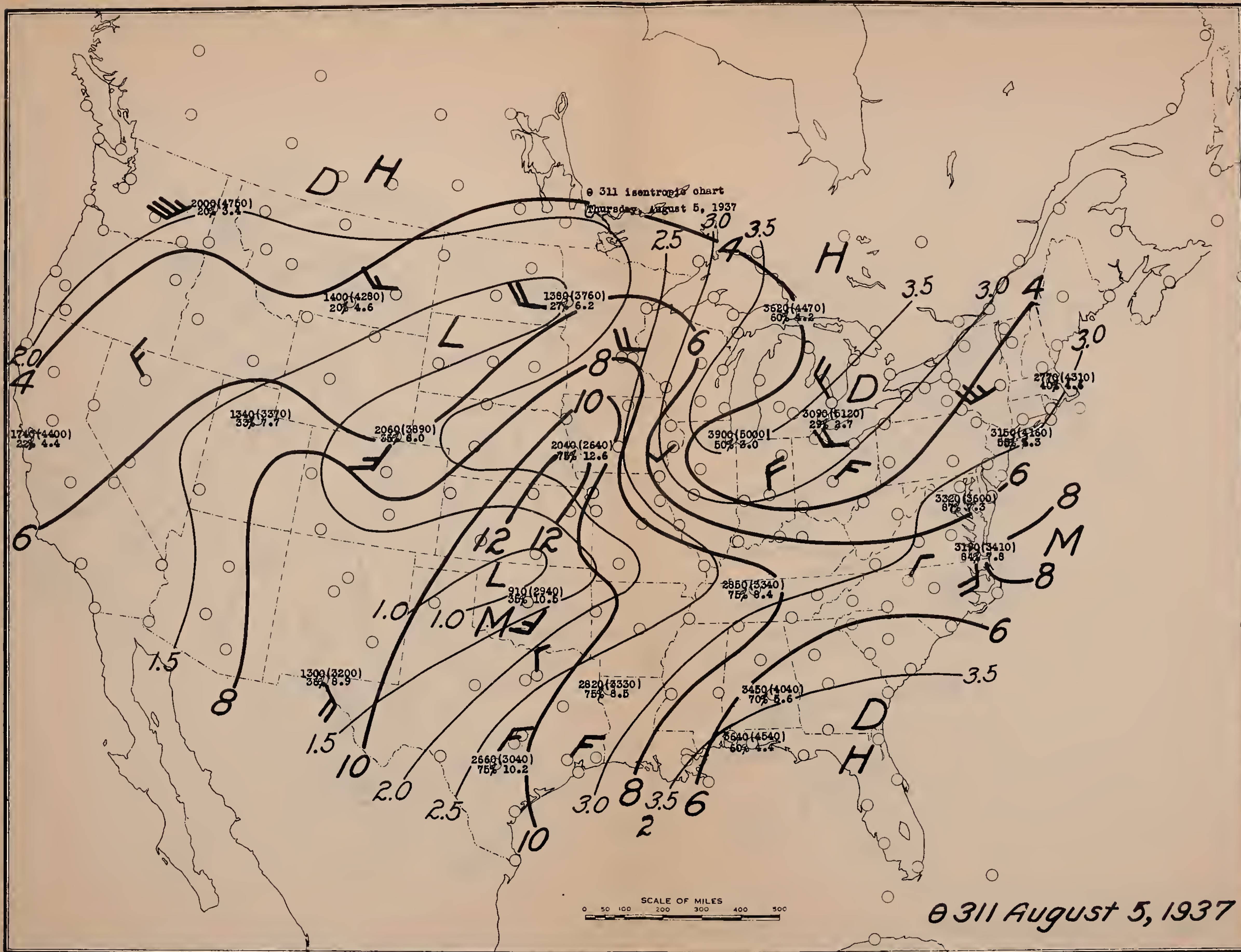



Pressure differences and change between 309 and 313 degree isentropic surfaces
Wednesday, August 4, 1937
90
90
30
30
20
C
U
C
C
C
D
S
D
S
70(50)
110(32)
16(-54)
12(--)
78(-17)
90(25)
80(-24)
55(-5)
55(-9)
63(5)
56(-24)
21(--
30(-15)
20(-50)
65(-63)
65(--)
70(-40)
83(18)
SCALE OF MILES
0 50 100 200 300 400 500
August 4, 1937


θ 311 isentropic chart
Thursday, August 5, 1937
2000(4750)
1400(4280)
20% 4.6
1380(3760)
27% 6.2
3620(4470)
60% 4.2
2770(4310)
1340(3370)
33% 7.7
2060(3890)
2040(2640)
75% 12.6
3900(5000)
50% 3.0
3090(5120)
3150(4160)
3320(3600)
3190(3410)
910(2940)
2850(3340)
75% 8.4
1300(3200)
2820(3330)
75% 8.5
3450(4040)
70% 5.6
3640(4540)
50% 4.4
2660(3040)
75% 10.2
SCALE OF MILES
0 50 100 200 300 400 500
θ 311 August 5, 1937

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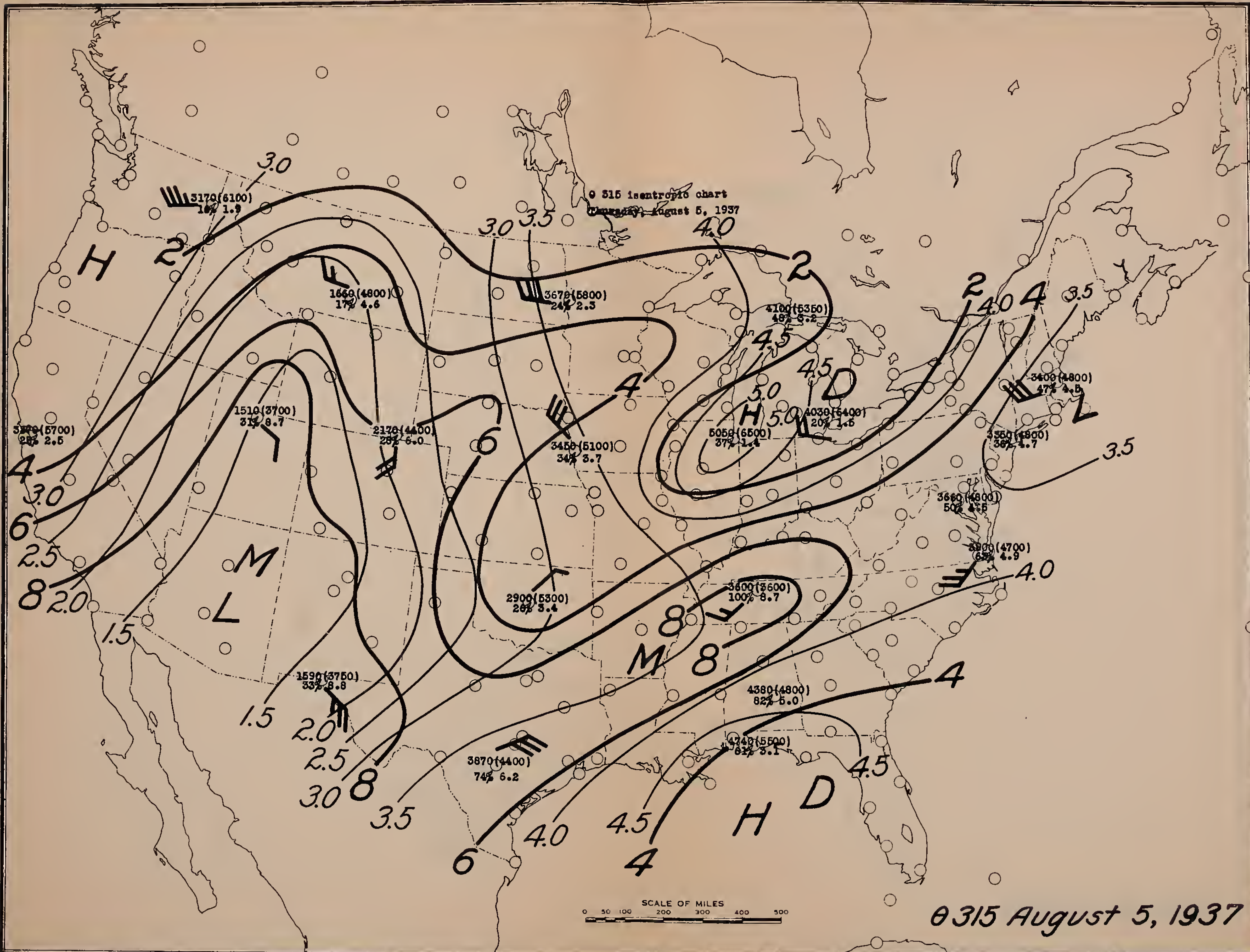
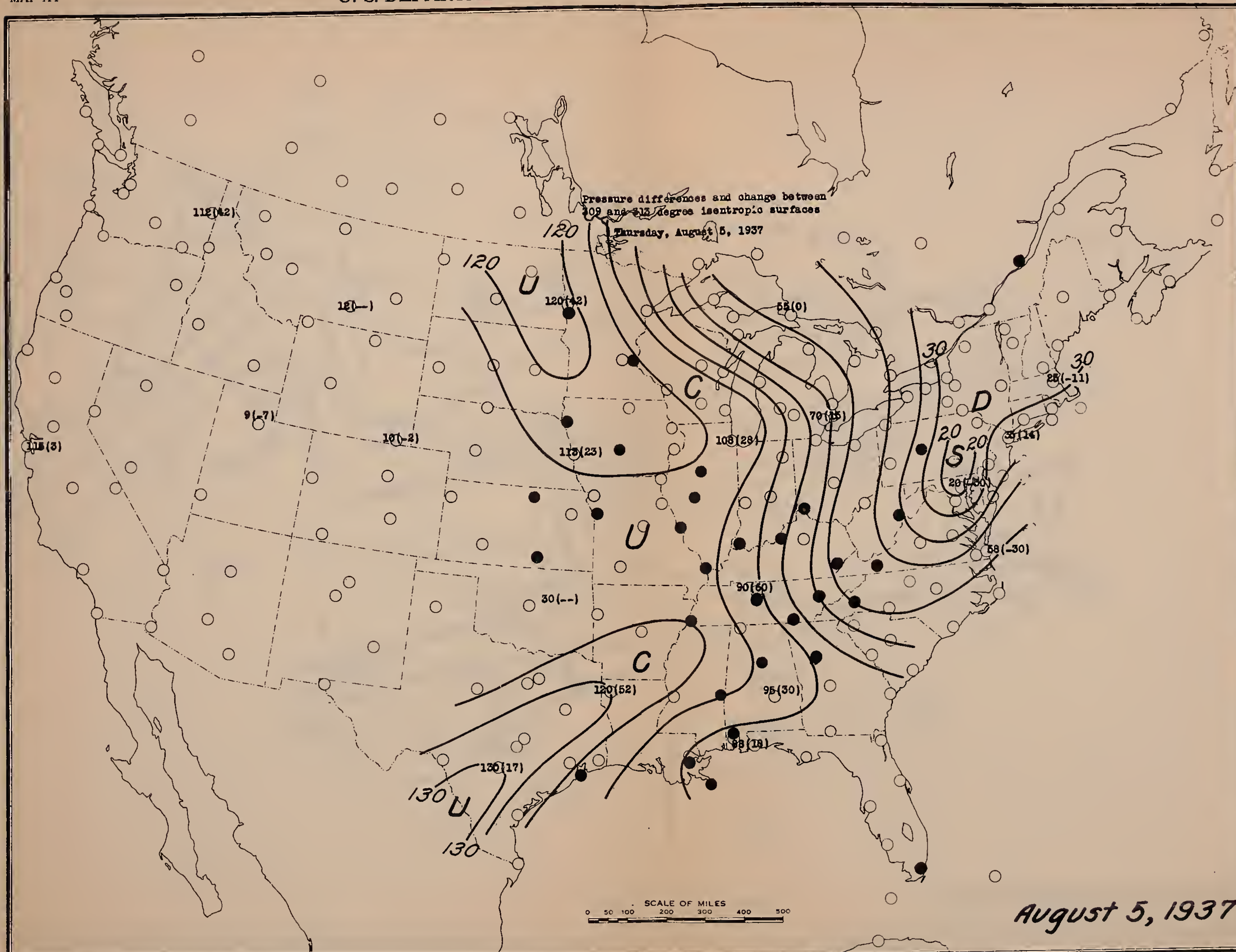
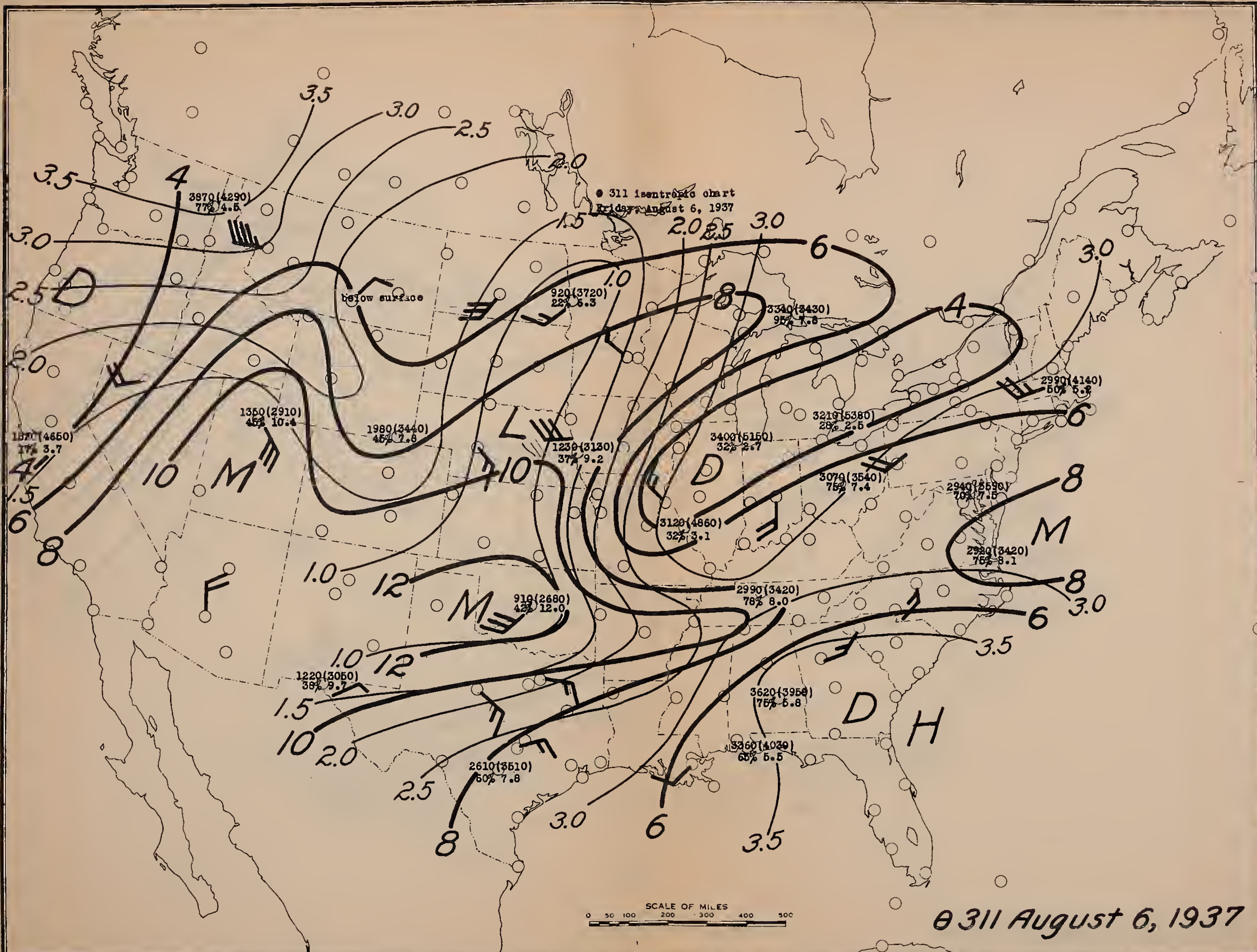



Pressure differences and change between
309 and 313 degree isentropic surfaces
Thursday, August 5, 1937
120
120
U
120(42)
112(42)
55(0)
C
70(15)
30
30
25(-11)
D
20
S
20
9(-7)
10(-2)
113(23)
108(28)
U
90(60)
58(-30)
30(--)
C
120(52)
95(30)
130(17)
130
U
130
SCALE OF MILES
0 50 100 200 300 400 500
August 5, 1937


θ 311 isentropic chart
Friday, August 6, 1937
below surface
SCALE OF MILES
0 50 100 200 300 400 500
θ 311 August 6, 1937

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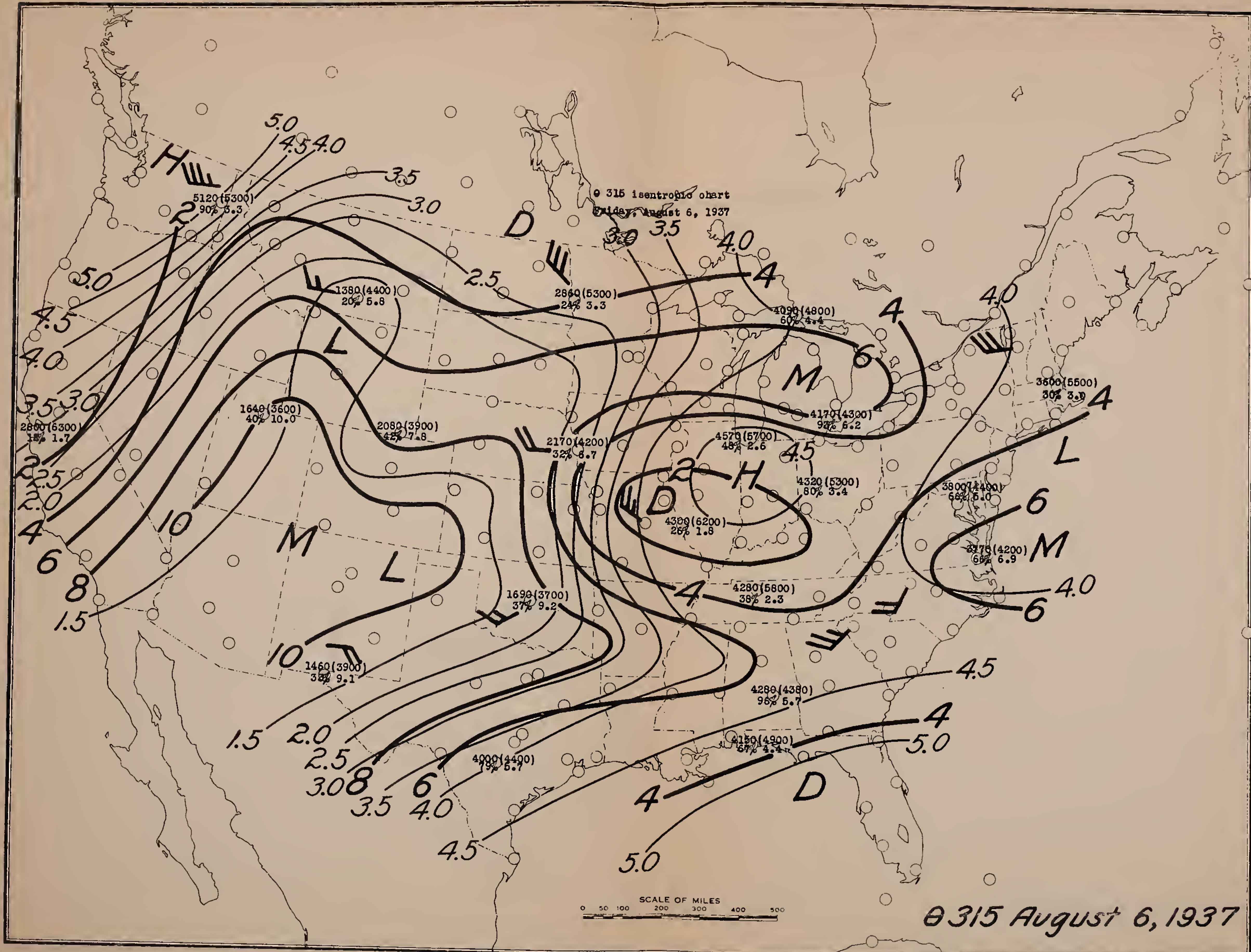

θ 315 August 6, 1937

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